AUTOMATIC CONTROL FOR WASTEWATER TREATMENT SYSTEMS

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Abstract

An investigation of the application of automatic control systems to wastewater treatment plants has shown this type of plant operation to be successful with savings in operating costs, energy, repairs and maintenance, and data logging. Inputs of periodic disturbances or perturbations produce deviations in plant operating conditions which reduce plant efficiency or result in a plant upset. The application of the feedback principle allows controllers to compensate for the disturbance and regulate the output at desired set points.

An example of optimal control design based on data from a local treatment plant is used to determine the optimal controller gain matrix as well as simulating plant behaviour and producing design information.

Computer control of plants is considered to be a major step for future plant operation as well as central control of several remote plants by a single computer facility.

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1.0 INTRODUCTION

The operation of a typical wastewater treatment plant requires an expenditure of energy to produce an effluent which meets the standards for which the plant has been designed. Examination of energy requirements is now considered to be a necessity in the design of treatment plants and for their operation.[1-3] The design of new plants can incorporate the latest advances in technology with respect to flow configuration, unit operations and hydraulics. Older existing plants are less amenable to the application of new technologies and may be heavy energy consumers. The utilization of automatic controls provides a means of regulating and minimizing energy requirements and costs for plants already in operation and for those in the design stage.

Automatic process control is used primarily because it results in economy of operation of the process, and in most cases, it more than pays for the expense of the control equipment. According to Eckman,[4] "automatic control is the maintenance of a desired value of a quantity or condition by measuring the existing value, comparing it to the desired value, and employing the difference to initiate action for reducing this difference."

The advantages, in general, to the use of automatic controls are:[4]

(i) Improvement in quality of products or effluent streams;

(ii) Improvement in quantity or number of products;

(iii) Improvement in uniformity of products;

(iv) Savings in processing chemicals and materials;

(v) Savings in energy or power requirements;

(vi) Savings in plant equipment.

The question of high capital cost is usually quoted as a disadvantage to implementation of a control system, but references to be discussed later show that economic gains within the first year of operation are feasible and can pay the equipment costs in some cases.

1.1 Controls in Wastewater Treatment Systems

The operation of wastewater treatment plants requires more skilled handling than most industrial processes because of the large temporal variation in wastewater flow and composition.[5] In comparison to industrial processes, most wastewater treatment plants are in a primitive state with respect to process operation. The results of poor plant control are usually observed as process failures such as the bulking of activated sludge and "sour" anaerobic digesters. Plant treatment efficiency varies greatly from plant to plant and especially from day to day and hour to hour in the same plant. BOD removals can vary from 60 to 95 percent efficiency daily within the same plant.

1.2 Manual Control and Automatic Control

Manual control in a wastewater treatment plant requires the operator to determine the status of the treatment or measure the quality of the product.[6] Any deviations from desired or required operating conditions are manually corrected by changing those variables which can be controlled or varied. If these corrections result in an improvement, the operator continues to make adjustments until he feels the process is operating properly. The action of observing the effluent and then making a change, such as opening or closing a valve, etc., is referred to as "feedback control". Figure 1 illustrates this principle. In most cases, this feedback loop is implemented by using automatic recording instruments as a substitute for human sensing, and produce a chronological record which will indicate trends and shock loadings. Sensing and measuring instruments have undergone major changes and can be considered more reliable than earlier sensors, thus making them well suited for feedback application.

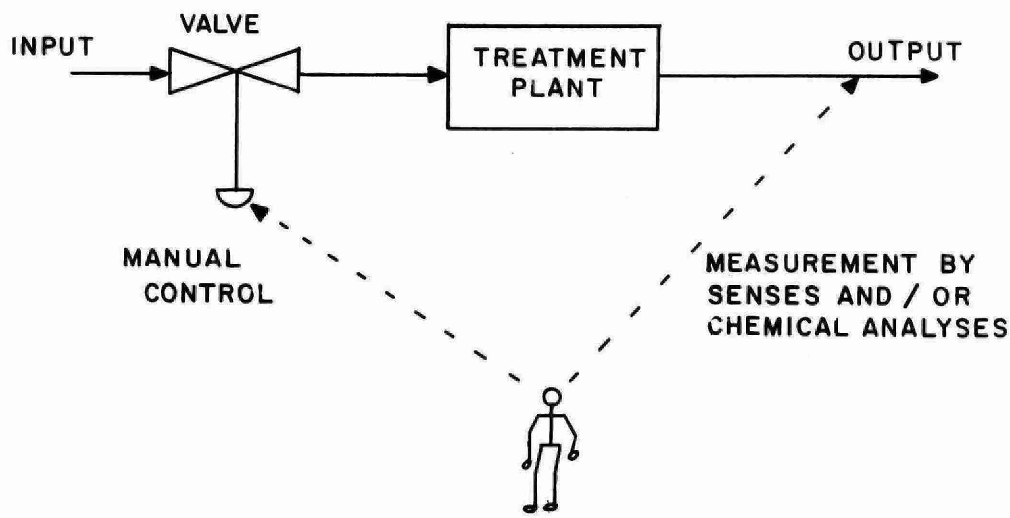

FIGURE 1. MANUAL PLANT OPERATION [6]

Automating the feedback system removes the operator from the judgement and adjustment process, allowing the automatic controller to maintain the desired set points by performing the required operations such as opening or closing valves automatically and proportionately. The general plan for an automatic control system is illustrated in Figure 2. In this type of operation, an operator is still required for monitoring and adjustment of set points.

1.3 Computer Control

In 1970, there were approximately 12 treatment plants in the U.S. using computers [6] for process control. Their use consisted mainly of data processing and monitoring, and some form of process control for conventional modes such as on-off ("bang-bang") control and proportional control. One detriment to computer control, or "direct digital control," was the cost of the computer in addition to the cost of the control instrumentation. With the advent of integrated circuits and microprocessor chips, the cost of computer hardware has fallen drastically. The controls for a whole plant can be placed on one integrated circuit chip which is linked to the sensors and control valves, and to the central processing unit (CPU). The basic cost of a CPU with a TV typewriter monitor is now less than $1,000 and the cost of chips in the $5 to $20 range. The application of computer control for optimizing the system is ideal, since a plant could be controlled to produce a more consistent effluent at a minimum operating cost and for a minimum energy requirement. Data logging can be done automatically during control. Upsets can be minimized regardless of the type of input or loading to the system.

Addition of computers to automatic control installations allows data processing and monitoring to be carried out as well as optimal control with a further reduction of operating costs and energy saving. Optimal control is the goal toward which most control users are striving. The "optimum" may refer to plant control with a minimum cost associated with a

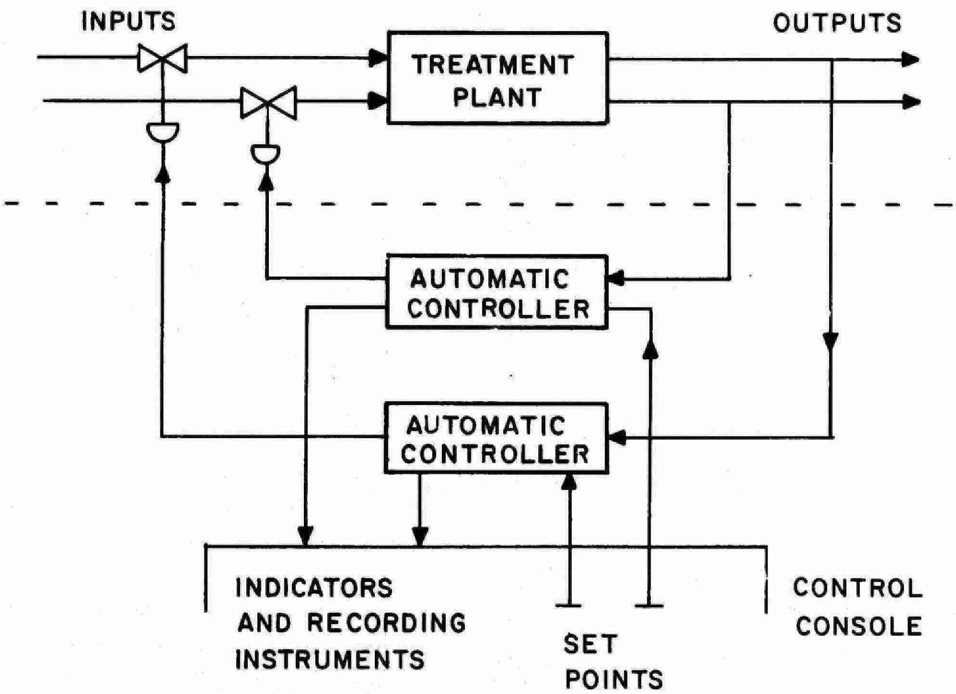

FIGURE 2. AUTOMATIC CONTROL SYSTEM FOR A WASTEWATER TREATMENT PLANT (6)

requirement that the effluent BOD_5 be restricted to 10 mg L^{-1} or less. Another optimum may be a minimum amount of operating energy to achieve a required effluent TOC or BOD. The computer in this case would take into account the values of all significant process variables and calculate the new set of conditions for achieving an optimal state. The computer would then initiate the changes necessary to the correct extent to attain the optimal.

1.4 Process Dynamics and Simulation

In designing process control systems and optimal control systems, the design of the wastewater treatment plant must be determined from calculations based on its dynamic behaviour, rather than on a steady state balance as customarily used. A dynamic analysis allows the inclusion of unsteady state phenomena, such as diurnal variation and shock loading. In this manner a more realistic plant system may be designed with and without the inclusion of controllers. The process dynamics of the system are usually represented in the form of a mathematical model. A dynamic model for a system is generally in the form of an ordinary differential equation which may or may not include controls within the equations. Solution of the differential equation(s) can be obtained very easily using a numerical subroutine on a computer, thus generating results for any possible situation of inputs and control. If a conventional type of control is used, the effluent response can be determined immediately from this integration subroutine. If an optimal control is desired, an optimizing subroutine can be used with the integration to obtain the desired control as well as other system design parameters. The results obtained by these techniques can be used for the system design as well as the future operating criteria.

2.0 INSTALLATIONS UTILIZING CONTROL SYSTEMS

All examples described in this section and referenced have advocated control systems because of the high degree of success. The degree of automation for the references cited varies from plant to plant, from simple electro-mechanical controllers to sophisticated computerized systems. The specific program sequences of control were different as were the plant objectives. In all cases, the results and plant performances exceeded the expectations with respect to costs, energy, effluent quality, sludge production, upsets and personnel participation.

2.1 Description of Applications

The first example of automated wastewater plants is one which is described by Martin [7] as being inexpensive, non-exotic and non-computerized, and utilizes electromechanical controllers. This type of control was applied to two New York communities; Sherburne and Alfred. The systems had been on stream for three years prior to publication of the above-mentioned paper and are treating 0.34 and 1.0 mgd respectively. These are trickling filter plants of secondary and tertiary levels respectively. Without going heavily into the details of the control mechanisms, the operating cycle involves:

- drawing supernatant from the sludge digester;
- restarting sludge circulation, mixing and heating;
- opening valves to draw sludge from first settling tank sludge hopper into digester;
- starting sludge transfer pump;
- sensing sludge density change by photoelectric cells across a sight glass in the sludge line;
- opening valve to hopper #2 and closing valve to hopper #1;
- shutting off sludge transfer pumps and related valves;
- operating sludge scraper on an intermittent basis until the time for repeat of cycle.

Alarms are used to indicate malfunctions. The advantages of this system were described as; permitting more efficient plant operation, relieving the operator of routine tasks, and allowing sludge handling to be automatically performed around the clock that otherwise required his presence in the plant.

This system was installed for about $25,000, and it was estimated that about one-half the operator's time was made available for other work for an approximate savings of $5,000 per year.

An example of a computer-controlled wastewater facility is the Morris County Plant in north central New Jersey. [8] The plant is a 0.175 m^3/s (4 mgd) activated sludge facility with a newly constructed 0.53 m^3/s (12 mgd) addition. This plant has been operational for one year. The flow configuration of the plant involves pumping, grit removal, primary settling, aeration, secondary settling and chlorination. The sludge flow consists of gravity primary thickeners, air floatation waste thickeners, blending tanks, vacuum filtration, and multiple hearth incineration. The tertiary addition comprises nitrification, denitrification, filtration, and chlorination.

The reasons, in this case, for a computer installation at this facility were given as follows:

1. the complexity of the added tertiary facility;
2. the size of the complete facility;
3. the desire for greater efficiences for the overall system and for economical operation;
4. the ability to balance the old system with the new additions;
5. the fear that large amounts of industrial wastes might upset the entire facility;
6. new treatment regulations.

Control and plant operation are done by the operator at a computer console. For example, the operator has the option of varying the raw wastewater flow so that either the existing facility or the new facility can take any proportion of the incoming flow, or any unit can take a constant flow with flow variations taken by the rest of the units. Flow control is monitored by a magnetic flow meter and controlled by a motor-operated sluice gate.

Operation and control of the primary sludge system is tied in with a control loop which optimizes pumping according to measurements by a sludge density sensor. For the activated sludge system, the computer totals the wastewater flow entering the aeration tanks and compares it with the return sludge flow being pumped and to the preset ratio. The resultant output signal is directed to the return sludge pump for control of total return sludge. The pumps speed up or slow down according to the output signal.

On a power saving basis, when the computer senses that two pumps operating at low speeds could be replaced by one pump operating of high speed the appropriate action is taken by the computer.

The waste sludge also passes through a sludge density meter which signals the computer if the solids content of the sludge falls below the minimum thickness desired to waste. If this condition occurs, the computer alerts the operator and shuts down the waste sludge system. The benefits involved in this particular system are cited as:

(i) providing equipment identification with preventative maintenance schedules;

(ii) records of breakdown repairs;

(iii) records of pump running time to avoid wear and tear on any given pump;

(iv) assisting the operator on data logging;

(v) providing print-outs of all operating parameters;

(vi) performing of accounting and financial functions with budget control;

(vii) indicating when to order chemicals such as ferric chloride, lime, hypochlorite, etc.

(viii) maximizes treatment efficiences while meeting water quality objectives.

Another computer-controlled system is the John E. Egan Water Reclamation Plant for the City of Chicago, Ill. [9] This \$43-million facility, completed in 1976, provides tertiary treatment for a flow of 2.5 m^3/s (50mgd) and primary treatment for up to 5.5 m^3/s (125 mgd) of mixed stormwater and sewage. In this case, the State of Illinois required that ammonia removal capability be incorporated into the plant design. The effluent limits imposed upon the design of the plant were:

BOD_5:	4 mg/L
SS :	5 mg/L
NH_4-N :	2.5 mg/L

A major design requirement was the implementation of the maximum amount of automation in plant operation. Computer use was also favoured because 175 process control parameters had to be monitored and logged.

The features of this facility are:

(i) large scale plant design incorporating the two-stage activated sludge process for controlled biological nitrification of nitrogenous wastes;

(ii) biological denitrification on high-rate dual-media (sand and anthracite coal) filters;

(iii) phosphate removal by addition of alum in the first-stage aeration and sedimentation basins;

(iv) use of digital computers for control of several subsystems, including chemical feed, aeration sludge pumping, filter backwashing, sludge digester loading and unloading and for controlled scheduling of operation and maintenance functions and report generation.

(v) use of a gas turbine to continuously operate one large blower, the use of which will cut peak electrical power usage.

The waste exhaust heat is recovered in a waste heat boiler for general heating use.

The functions performed by the computer and associated instrument systems are:

- monitoring performance of 4 centrifugal blowers, including a 1500 hp gas turbine for approach of surge conditions; providing alarm warnings, summing air requirements, computing air-to-sewage ratios for operating control and report generation;
- determining quantity of return sludge to aeration tanks based on the preset concentration of MLSS and raw sewage flow;
- backwashing of filters based on excess loss of head or high effluent turbidity, whichever occurs first;
- distributing thickened sludge to digesters (to ensure uniform loading);
- discharging sludge from digesters based on loading and operating schedule.

The computers used are 16 bit work machines, each with 32 kbyte core memory and a 2.5 Mbyte disc. A communication link is provided together with a routine in which the memory of the offline machine is updated every 15 minutes. Figure 3 is a block diagram of the computerized system. The advantages for this plant of computer operation and control are the same as discussed previously. The major advantage cited for this plant is reliability.

Another system in Bloomington, Minnesota was designed for municipal water treatment, pumping and monitoring the cities storm and sanitary sewer operation.[10] Its control system is entirely solid state, and automatically operates the 0.26 m^3/s (6.0 mgd) facility continuously 24 hours per day. In addition, to controlling and monitoring, the plant maintains peak efficiencies at minimum energy expenditure.

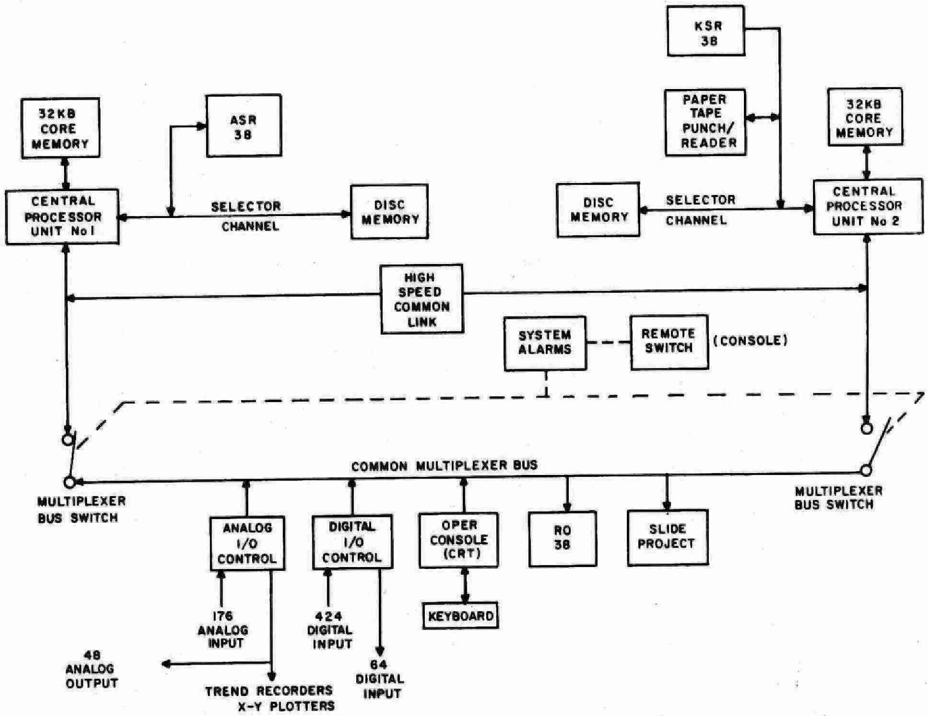

FIGURE 3. LAYOUT OF CHICAGO PLANT (9)

An example of another direct digital control (DDC) application is the San Jose/Santa Clara water pollution control plant in California. This plant has the capability of treating 7 m^3/s (160 mgd) of raw sewage. The computer in this case was a Fischer and Porter Series 3000 system including all hardware and software. Of the benefits, treatment efficiency was cited as being first, since perfect mass balances could be attained hour by hour with no upsets. The conservation of energy was substantial. The 2500 hp engines that supply air to the aeration and nitration tanks accounted for the greatest single item of energy consumption. With DDC, control is automatic. The computer receives a continuous measurement of air in the process based on input DO or DO in the tank. The computer controls the blower engine speed in increments or decrements according to need. Addition of chemicals is monitored and controlled resulting in a conservation of chemicals and thus a cost savings. Management information on all stages of operation are available at all times including diagrams of all process areas.

The conclusions of the authors on DDC of wastewater plants are as follows:

- DDC is a far better way to control a large wastewater treatment plant than any combination of analogue and manual control;
- the design, installation and start-up of a DDC system is straightforward, considerably easier, and less costly than one might expect.

Other cities in the U.S. involved in plant automation are Denver, Colorado, Atlanta, Ga., Monroe County, N.Y., Metropolitan Seattle, Wa., and San Francisco, Ca. [12] Further details on other applications of automation can be found in papers by Flanagan, [13] Popalisky and McMurtey, [14] Sherrard,[15] Andrews, [16] Ricoy and Matotan, [17] and Heckroth, [19] Belick and Van Kirk, [11] and Kron. [18]

An interesting and worthwhile study was undertaken by Genthe _et al_ [20] who examined case histories of automatic control of dissolved oxygen for 12 wastewater treatment plants. This study is complete with plant data and flow sheets for each plant investigated. Their conclusions indicate that a substantial savings in aeration energy usage resulted from 9 of the 12 plants. Many other benefits and improvements were noted. "In general, the case studies indicate that automatic DO control is justified for plants having considerable fluctuations in input loading, adequate aeration capacity and adequate aerator turndown without loss of efficiency."[20]

Other major worldwide applications can be found in a special issue of _Water Research_, 1972. [21]

2.2 Hardware and Software

The question that usually arises in any preliminary consideration of wastewater treatment automation, especially computer control, is what type of control hardware will be required and how much. The Hyperion sewage treatment plant in Los Angeles [19] provides the example of a large automated system to focus attention. It has a peak wet weather flow of 31.5 m^3/s (720 mgd) and secondary treatment is provided by an activated sludge system to a constant flow of 4.4 m^3/s (100 mgd). The plant occupies 144 acres and uses a digital multiplexing system for data transmission to the centralized control panels. The data transmission rate is 2,400 bits per second on a multiple party line of full duplex configuration. This system was chosen because it was more economical than an analogue system.

The computer control equipment consists of:

- 2 central processing units;
- 2 bulk memory units;
- 2 magnetic tape cassette units;
- 1 programmer's teletype;
- 8 monochrome alphanumeric TV typewriters;

- 2 printer plotters;
- a multiplexer control unit for the interplant telemetering system;
- an auto dialing unit, line adapter and model for the intraplant telemetering system.

The alphanumeric TV typewriters provide unit process status, normal and abnormal, and manual data input for each area control centre.

The computer uses vendor-supplied software in plain English. Application software includes data communications, data processing, direct digital control, logging and man/machine interface packages.

The data acquisitions subroutine determines which points are to be processed for different scan rates. It inputs the data, filters the raw data, linearizes and normalizes, generates alarms initiates the control sequence and interfaces data logging.

The control subroutine implements proportional-integral-derivative (PID) control, cascade operation of multiple loops, feed-forward linkage, dead time compensation, lead/lag compensation, and user algorithms.

2.3 Justification of Costs for Control Systems

The decision for implementing automatic control systems is usually based on some justification of the cost of automated control systems. The first major step is to get a feel for the approximate dollar amount of money that can be saved if the overall system operating efficiency could be improved by roughly 3% to 6%. Experience gained by the business data industry during the past decades suggests that an effective management information system should improve overall management effectiveness by at least 2% to 5% for essentially any justifiable application.

General cost justification considerations are:

1. Projected Capital Development Savings

The best insurance against over-design or under-design of additional capital facilities is better operating data.

2. Annual Chemical Expense Savings

Chemical costs can be quite significant especially in large treatment plants. A 3% to 6% chemical cost savings over a 10 to 15 year period could be substantial for any plant. Elimination of overfeeding is one major advantage along with chemical inventory and reorder times.

3. Annual Power Savings

Savings on energy requirements is one of the more noticeable effects of automatic control since power is directly related to the degree of control. Power reductions up to at least 10% can be achieved by optimal control.

4. Building a Case for Customer Rate Increases

Thoroughly logged data can powerfully influence arguments for rate changes since rate increase requests are usually based on subjective arguments.

5. Computer Reliability

It is difficult to assign a dollar value for reliability but improved reliability is a very real benefit. Automatically recorded data are not subject to human error or subjected to loss or misplacement.

3.0 SYSTEM DESIGN FOR OPTIMAL CONTROL

The design of an automatic control system is exceedingly difficult unless one attempts to obtain some idea of how the controls operate and their effect on effluent quality before implementation. One generally used technique is simulation. This allows one to explore the complete system operation under all kinds of loading conditions and input perturbations. It permits the determination of flow conditions, control requirements, sludge buildup, etc., as well as physical size and design configurations. Because the actual system operates under varying conditions, these effects can be accounted for in the model.

The operation of an aeration tank, for example, is a dynamic one because no steady state input ever exists for the system even though the system was most likely designed and sized on a steady state basis. Thus, shock loads and variable loadings do not allow the system to achieve the output specifications for which it was designed. Because the diurnal variation is cyclic, a steady state can never be achieved. In the case of a well run system the state variables behave in the form of a limit cycle which will be unstable if a perturbation such as a shock load is introduced.

Other typical problems encountered in biological waste treatment operation include process upsets and system instability resulting in the discharge of untreated wastes or poorly treated effluents into receiving waters. Instability is usually characterized by bulking sludges which settle poorly. Unstable operation can also result in the washout of the sludge with its organisms and produce a period of inefficient and unstable operation. Compounded with these problems is the changes in influent flowrate and the influent substrate concentration.

These difficulties can be observed in a simulation of a system and thus, corrections in design can be made. The instability problem

itself is one in which application of controllers can reduce to a great extent. In addition, to controlling the system, the operating costs can be reduced by optimizing the control behaviour. The next section illustrates the effects of using a controller in an activated sludge system and how plant performance can be improved.

4.0 PROCESS DYNAMICS AND MODELLING

In doing feasibility studies, a mathematical representation of the system is necessary in order that response for different conditions may be obtained. The resulting data can then be used for economic evaluation and choosing design and operating conditions. Too often, steady state equations are used because of their algebraic simplicity. Their application results only in steady state values which are never achieved due to the continually varying external disturbances. Proper design for variable inputs requires unsteady state analysis. The models themselves use only the basic equations and results of fluid mechanics, heat transfer, mass transfer, thermodynamics and kinetics, combined into general unsteady state mass, heat and momentum balances which give excellent representations, in the large, of the treatment system or unit under evaluation. With the correct assumptions, very complicated systems can be reduced or linearized without great loss of information. Because computers are smaller and cheaper, integration of large sets of differential equations can be done quickly and easily without an extensive background in the theory of differential equations.

4.1 Automatic Control and Optimal Control

No matter what type of control system is implemented there will be some improvement in the system operation. Application of simple proportional feedback control allows for gradual adjustments or rapid adjustments in the system to compensate for changes due to daily variations or shock loading. A little experimentation on gain and reset values

can produce outputs with low oscillation and rapid returns to set points. Optimal control design enables one to include costs and energy into the plant operation along with controlled effluent regulation to obtain a minimum or optimal performance criterion. The advantages of optimal control design fall firstly in the feasibility stage where performance indices can be compared when it comes to choosing a process or determining process variables. Secondly, in modifying an existing plant with a poor performance record, information can be obtained for best design modification conditions.

Of the optimal design techniques, the linear system design based on Pontryagin's Maximum Principle, and non-linear optimization by Direct Search are typical examples. Utilization of the Maximum Principle requires some mathematical preparation before putting the equations on the computer, but only one pass is required and computer time is low. Direct Search is relatively uncomplicated as only the state equations are required. Programming is relatively simple and inequality constraints can be handled with ease.

When multiple optima exist, the other search techniques may converge to a local optimum instead of a global optimum. The reliability of obtaining a global optimum is not only problem dependent but is also influenced by the choice of starting point, the size of the initial search region and the rate of reduction of the search region. The production of a gain matrix allows one to implement directly the gain values obtained on the system itself and thus obtain optimal system operation and performance.

The actual utilization of the Direct Search procedure involves only changes in the subroutines containing the state and disturbance equations for the different models and systems. Running time increases with the number of differential equations to be solved and to a lesser extent with the degree of complexity and the number of controls involved.

Overall, the method is easy to apply and results can be obtained with very little sophisticated mathematics.

5.0 APPLICATION OF CONTROL TO WASTEWATER TREATMENT SYSTEMS

As an example of a system which could be optimized, consider the activated sludge treatment system of the City of Cambridge (Galt).

The design parameters of this system are as follows:-

Design Flow	0.37 m^3/s (8.5 mgd)
Design Population	34,000
BOD - Raw Sewage	250 mg/L
- Removal	90%
SS - Raw Sewage	250 mg/L
- Removal	90%

The primary treatment steps consist of comminution, grit removal and primary sedimentation. The secondary treatment consists of single pass mechanical aeration in four 45.7 m x 9.1 m tanks with a retention time of 7.0 hr. Secondary sedimentation is carried out in two 23 m dia. x 3 m swd tanks with a retention of 2.64 hrs. The other steps involved are chlorination, sludge digestion and vacuum filtration.

On the basis of plant performance, the data in Table 5.1 were used to synthesize an optimal control.

5.1 Mathematical Model of an Aeration System [21]

It is now well established that the kinetics of an aerator or an aerobic reaction systems obey a Monod rate equation.[22] Monod kinetics are similar to Michaelis-Menten kinetics for enzyme reations.[23] The Monod rate equation describes the overall growth of a biological system.

The flow behaviour in aeration tanks is usually based on chemical reactor design and the type of fluid mixing; the continuous stirred tank reactor (CSTR) and the plug flow reactor (PFR) exemplify the two extremes of fluid mixing. For simplicity in using the aeration system as an example, the CSTR formulation is used.

TABLE 5.1. PLANT PERFORMANCE PARAMETERS

Flow:		
	average	5.2 mgd = 9.85×10^5 L/h
	maximum	8.7 mgd = 1.65×10^6 L/h
	retention	7 hours
BOD_5:		
	influent	170 mg/L
	effluent	13 mg/L
	Maximum influent	300 mg/L
SS:		
	influent	170 mg/L
	effluent	18 mg/L
MLSS:		
	average	3,000 mg/L
F/M		0.13
Aeration Tank Volume		6,627 m^3 (nominal) = 6.627×10^6L.

The system model used for the activated sludge system is similar to the one used by Angelbeck and Alam [24] except that the Monod equation is used to model the growth rate. The state equations are given by:

$$\frac{dx_1}{dt} = \theta^{(T-T_1)} \hat{\mu}_{T_1} \left[\frac{x_1 x_2}{K_s + x_2}\right] - \frac{d_3 u_1^{(1-f)} 10^6 x_1}{GAx_1^{(1-f)} d_2^f}$$

$$- k_d x_1 + d_3 d_1 \qquad \text{.......(5.1)}$$

$$\frac{dx_2}{dt} = d_3(d_2 - x_2) - \theta^{(T-T_1)} \hat{\mu}_{T_1} \left[\frac{x_1 x_2}{K_s + x_2}\right] /Y \qquad \text{........(5.2)}$$

with initial conditions

$$\begin{bmatrix} x_{1s} \\ \\ x_{2s} \end{bmatrix} = \begin{bmatrix} 3000 \\ \\ 13 \end{bmatrix}$$

where,

x_1 = the biomass concentration, (MLSS, MLVSS, etc.), mg/L

x_2 = the concentration of substrates or organic nutrients (BOD, TOC, etc.), mg/L

K_s = saturation concentration, mg/L

k_d = specific endogenous microbial attrition rate, h^{-1}

$\hat{\mu}_{T_1}$ = maximum specific growth rate, h^{-1} (at temperature T_1)

T = temperature, °C

θ = temperature correction factor

Y = substrate conversion yield factor, mg/mg

u_1 = the sludge recycle control

d_1 = biomass input disturbance function

d_2 = the substrate disturbance function

d_3 = the input flow disturbance function

The ramifications of using Monod kinetics for activated sludge systems have been discussed in the references.

5.2 Determination of the Optimal Control

The optimal control problem can be discussed in a rather general way which is applicable to more specific cases.

Suppose that the system under examination is an n^{th} - order dynamical system of the form

$$\dot{\underset{\sim}{x}}(t) = \underset{\sim}{f}[\underset{\sim}{x}(t), \underset{\sim}{u}(t), t] \qquad ......(5.3)$$

where:

$$\dot{\underset{\sim}{x}} = d/dt(\underset{\sim}{x}) \qquad ......(5.4)$$

with prescribed conditions at t_o, i.e.:

$$\underset{\sim}{x}(t_o) = \underset{\sim}{x}_o \qquad ......(5.5)$$

The problem is to minimize (or maximize) a performance index

$$I[\underset{\sim}{x}(o), t] = J + \int_{t_o}^{t_f} \phi[\underset{\sim}{x}(\lambda), \underset{\sim}{u}(\lambda), \lambda]d\lambda \qquad ......(5.6)$$

such that a control $\underset{\sim}{u}(t)$ brings the state at $\underset{\sim}{x}_o$ to the desired state $\underset{\sim}{x}^{\circ}(t_f)$ at some final time t_f (or to the origin if the co-ordinates have been translated to the desired state).

The performance index is only a device which is developed to contain both costs and benefits as they may be applied to a system. An effective traditional method for evaluating the performance of systems is cost-benefit analysis. However, the cost-benefit analysis does not lend itself to easy implementation through common modelling techniques. The traditional approach to the performance index is to construct a cost equation which contains both costs and benefits. The benefits are expressed in terms of negative costs. With such a performance index it is then possible to obtain the best solution by seeking to minimize the costs.

The performance index used in this example is,

$$I[x_1, t_f] = 0.5 \int_o^{24} q_{11}(x_1 - x^o_{1s})^2 + q_{12}(x_2 - x^o_{2s})^2$$

$$+ r_{11}(u_1 - u_{1s})^2 \, dt \qquad ....(5.7)$$

where,

x_{1s}, x_{2s} = the steady state values of x_1 and x_2

u_{1s}, u_{2s} = the steady state value of the control

For further details on the mathematics and theory of optimal control one should consult any of the reference texts by Athens and Falb,[25] Koppel,[26] Lapidus and Luus,[27] Bryson and Ho,[28] McCausland,[29] Zadeh and Desoer,[30] Ogata,[31] Sage,[32] Tou,[33] Bellman,[34] Pontryagin et al,[35] Gibson,[36] and Lee and Markus.[37] These references cover the basic concepts of state space, controllability and observability, linear and non-linear systems, stability and optimization.

The techniques used for optimization are numerous and are of different degrees of difficulty. Usually one tries to choose the simplest method or the fastest method depending on the nature of the problem. The details of the optimization methods may be found elsewhere.[25, 37, 38]

The optimization algorithm used in this study is the "direct search method" formulated by Luus and Jaakola [39] and applied for determination of the optimal control law for non-linear systems.[40] The main advantage of this technique is its simplicity and its ability to obtain a global optimum.

5.3 Influent Disturbance Functions

The influent disturbance functions are the transients in flow and substrate concentration which cause the system to deviate from the steady state values. Generally, they can be of any form such as pulses,

step functions or sinusoidal functions. No matter what the specific form of the disturbance is, the optimal controller should minimize the effect of the disturbance and return the system to its steady state conditions without introducing any system instabilities. Sinusoidal functions were chosen based on the average and maximum conditions listed in Table 5.1.

From the values of flowrate, Q, and aerator volume, the retention time, $\bar{t}$ is:

$$\bar{t} = 1/(Q/V)$$

$$1/\bar{t}_{av} = 0.1486\ h^{-1} \qquad (\bar{t}_{av} = 6.73\ \text{hr.})$$

$$1/\bar{t}_{max} = 0.2487\ h^{-1} \qquad (\bar{t}_{max} = 4.02\ \text{hr.})$$

Based on the average and maximum flows, the input flow disturbance is assumed to be of the form

$$d_3(t) = 0.1486 + 0.1 \left\{\sin\ [2(2\pi t/18)]\right\} \exp(-0.213t) \qquad \text{......(5.8)}$$

for a period of 18 hrs. A plot of this disturbance is shown in Figure 4. Similarly, the BOD_5 input disturbance is of the form

$$d_2(t) = 235 + 65\ \sin(2\pi t/18 - /2) \qquad \text{......(5.9)}$$

and is shown in Figure 5. The method of control for this system is return sludge control. The recycle sludge flowrate is based on the feedback control law of the form

$$u_1(t) = g_{11}x_1 + g_{12}x_2 \qquad \text{......(5.10)}$$

where x_2 and x_1 are the effluent BOD_5 (TOC, TOD) and MLSS; the parameters g_{11} and g_{12} are the controller proportional gain values. The value of x_2 can be continuously monitored as TOC or TOD while x_1 can be measured continuously using suspended solids meters such as those manufactured by Biospherics Inc., Partech, Caltrol Ltd., or Eur-Control. These sensors are self cleaning and have shown some success in monitoring suspended solids.

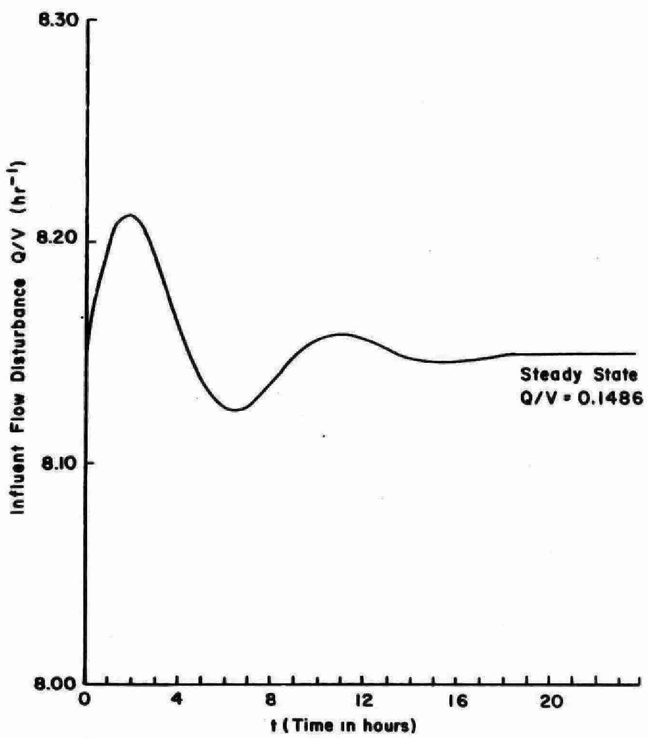

Figure 4. Influent Flow Disturbance, Q/V as a Function of Time

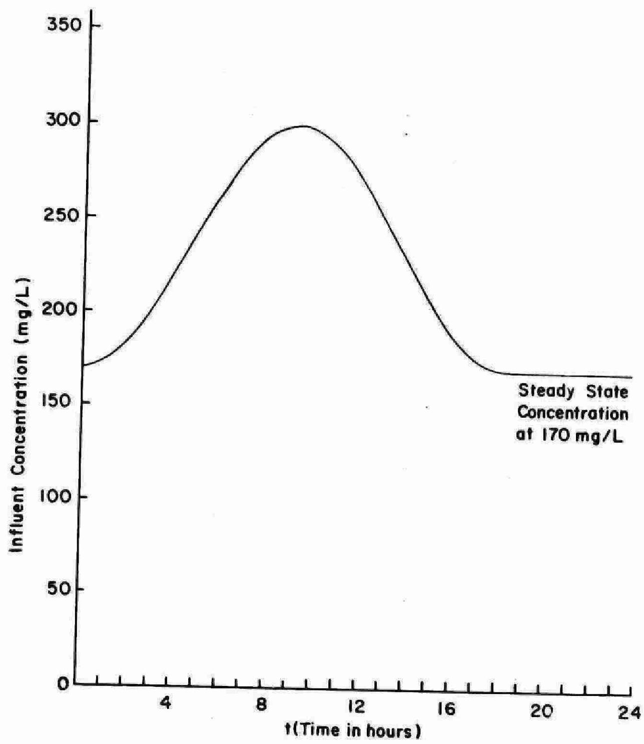

Figure 5. Influent Concentration with a Disturbance for $0 < t \leq 18$ hr.

5.4 Behaviour of Uncontrolled Systems

Using the two disturbances and a sludge return rate of 0.41, the effluent concentration and the MLSS follow the behaviour shown in Figure 6. With the disturbances applied, the effluent BOD_5 rises to a fairly high value and does not return to the desired value of 13 over the 24 hour period. The MLSS deviates well below the design value of the system and does not recover to the value of 3,000 before the next disturbance will be applied. With a constant value of $u_1 = 0.60$ for the sludge return rate, the result (Figure 7) for the effluent BOD_5 are somewhat better with a final effluent value of 11 mg/L. The MLSS continually rises producing a higher concentration of MLSS in the aeration tank. If constant values of u_1 are used, the major objective is a good quality effluent without any other considerations being involved.

5.5 Behaviour of Controlled Systems

In a controlled system we wish to maintain the effluent concentration and the MLSS as close as possible to the design or set point values. At the same time, we wish to minimize the amount of control required to do this. Utilization of a cost-performance index allows us to do this. The performance index in this case is of the form

$$I = 0.5 \int_{0}^{t_f} [(x_1 - 3000)^2 + (x_2 - 13)^2 \times 10^4 + (u_1 - u_{1s})^2]dt \qquad \ldots\ldots(5.11)$$

where u_{1s} is the control set point and 10^4 is a cost weighting factor.

The variations in MLSS and BOD_5 concentrations are shown in Figure 8. The MLSS is maintained fairly close to its set point and the BOD_5 peaks at a maximum of 22 mg/L and returns very quickly to the set point region. The return sludge control ratio and the waste ratio behave as in Figure 9. The values of the ratios are determined at finite sampling times so the control is varied in a stepwise manner. This is the optimal control required to regulate the MLSS and the effluent.

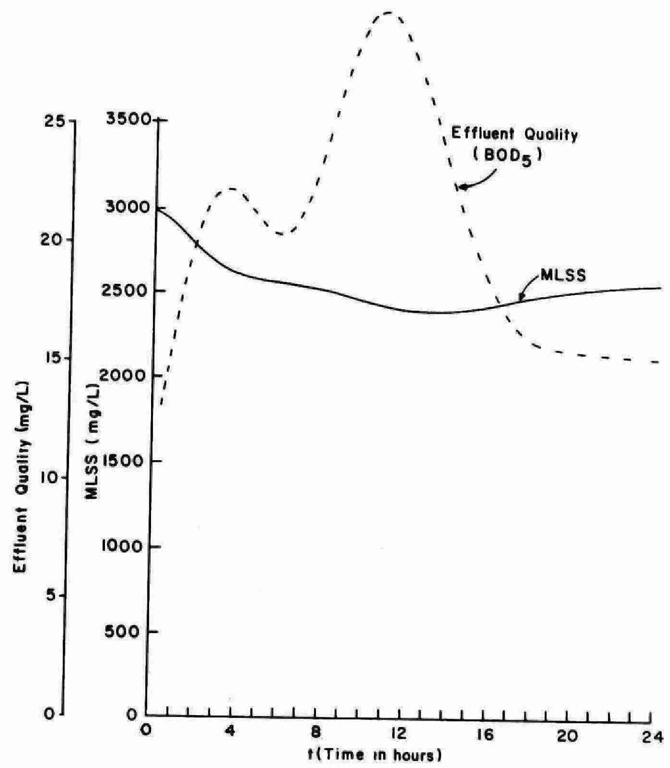

FIGURE 6. VARIATION OF EFFLUENT QUALITY AND MLSS FOR UNCONTROLLED SYSTEM WITH RETURN SLUDGE RATIO FIXED AT 0.41

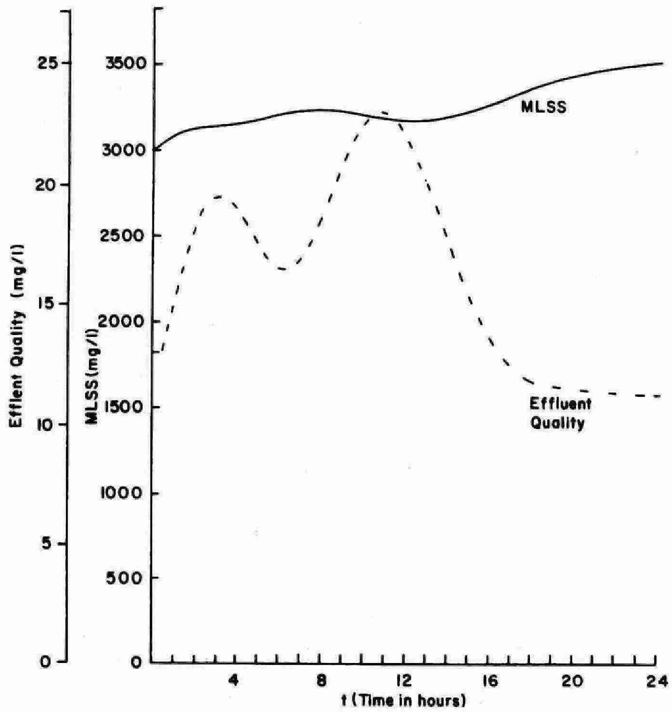

FIGURE 7. VARIATION OF EFFLUENT QUALITY AND MLSS FOR UNCONTROLLED SYSTEM WITH RETURN SLUDGE RATIO FIXED AT 0.60

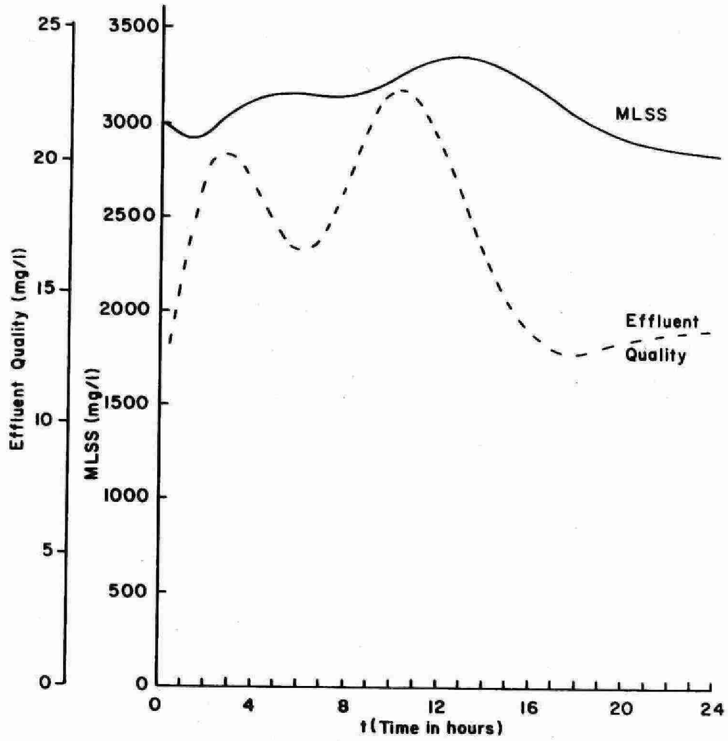

FIGURE 8. VARIATION OF EFFLUENT QUALITY AND MLSS FOR CONTROLLED SYSTEM WITH RETURN SLUDGE CONTROL

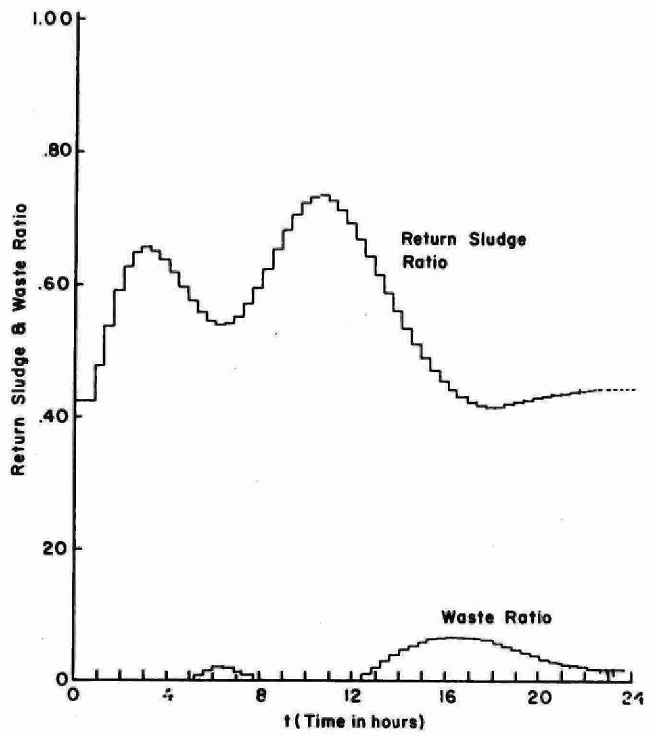

FIGURE 9. RETURN SLUDGE RATIO AND WASTING RATIO VARIATIONS FOR OPTIMAL CONTROL USING SLUDGE RATIO AS CONTROL

A comparison of the performance indices for the two uncontrolled systems and the controlled system is shown in Table 5.2. For the three situations examined the variable control will produce the optimum.

5.6 Control by Food-to-Microorganism Ratio

Another control policy formulation which can be utilized is the food-to microorganism (F:M) ratio technique. This method involves keeping the F:M value constant at a desired set value of F:M, where F:M may be defined as

$$F{:}M = \frac{(Q/V)(L_i) \times 24}{MLVSS}$$

where:

$$L_i = \text{input } BOD_5$$

For the design conditions imposed on the Cambridge plant, F:M should be maintained at 0.23. The performance index required to be minimized is

$$I = S_{11} 0.5 \int_0^{24} \frac{1}{t} \left\{ \left(\frac{d_2}{0.8x_1}\right) x\ 24 - F/M \right\}^2 dt$$

$$+ S_{12} \times 0.5 \int_0^{24} (x_2 - 13)^2 dt + S_{22} \times 0.5 \int_0^{24} (u_1(t) - u_{1s})^2 dt \qquad \text{......(5.12)}$$

where S_{11}, S_{12} and S_{22} are weighting factors.

The results for x_1 and x_2 and the controls are shown in Figures 10 and 11.

The MLSS rose fairly high, following the return sludge ratio and decreased when the disturbances were removed. The effluent BOD had a smaller variation than the previous controls policies and settled out at a BOD_5 of approximately 11.0. The behaviour of the system now approaches what is desirable for this type of operation.

TABLE 5.2. PERFORMANCE INDEX COMPARISONS

System	Return Sludge Ratio	Performance Index
Uncontrolled	0.41	9.225×10^8
Uncontrolled	0.6	3.279×10^8
Controlled	variable	1.809×10^8

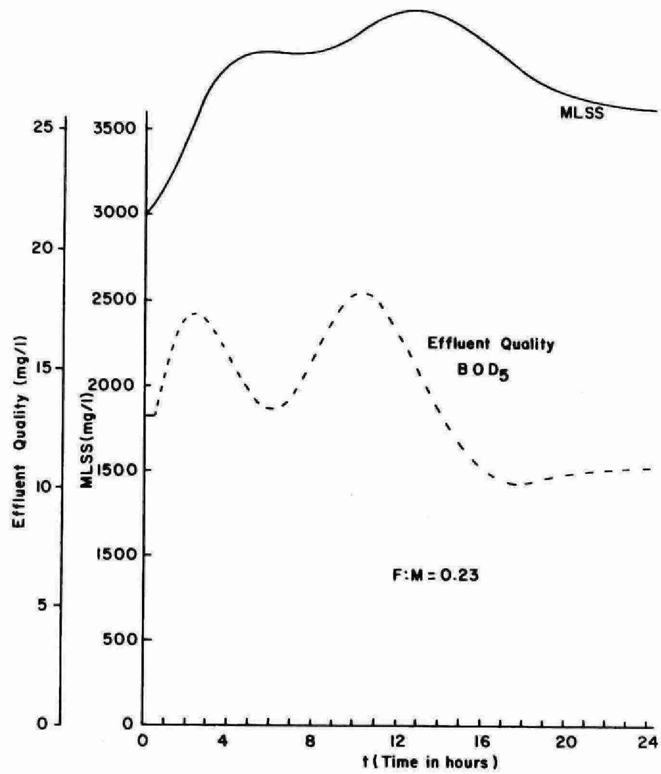

FIGURE **10.** Variation of Effluent Quality and MLSS for Optimal Control using a Fixed F:M Ratio

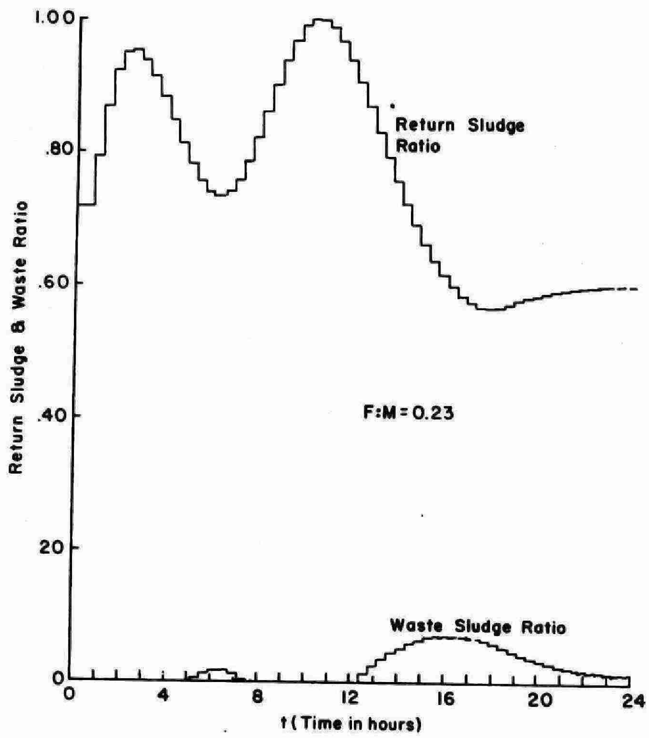

FIGURE 11. Return Sludge and Waste Ratios for F:M = 0.23

5.7 Discussion of Optimal Control Synthesis

The two control synthesis examples discussed above are basically similar in their method of obtaining the optimal control; i.e., by recycle sludge control, but the performance indexes differ. This is a reflection of what one wants as an objective for the effluent requirement or the cost of the control, or both. The performance index of Equation (5.11) weights the deviations of the actual values of the sludge and substrate produced by the system from their desired or equilibrium values and includes a weighting on the control action to minimize energy demand by the controller. This can be considered as the case where design data or government guidelines have been imposed on the plant operation. Equation (5.12) is similar to Equation (5.11) except that the first term involves the deviation of the F:M value from the steady state value of F:M. This performance index does not include the deviation of the sludge concentration but only the substrate concentration. The sludge concentration is then based on the F:M value and the control system attempts to keep this value constant.

Figure 9 shows the control variation required to minimize the performance index. The control law governing this variation is given by Equation (5.10). Concurrent with the determination of the system optimal trajectory and control behaviour is the computation of the controller proportional gain values g_{11} and g_{12}. For the control variation of Figure 9, $g_{11} = 2.316 \times 10^{-6}$ and $g_{12} = 3.19 \times 10^{-2}$, thus producing a performance index of 1.809×10^{8}. The control variation of Figure 11 based on F:M control was solved for proportional gain values of $g_{11} = 5.307 \times 10^{-7}$ and $g_{12} = 5.501 \times 10^{-2}$ for an optimal performance index value of 2.44×10^{5}.

In an actual operating system the values of the controller gain matrix would be determined by a computer and these values would be transmitted to the controller which would then maintain the system at the desired control settings and keep the performance index at the minimum.

The gain values could also be set manually if there is no link between the computer and the controller.

The synthesis of an optimal control also results in a simulation of the system and a sensitivity analysis. Thus, in doing this type of analysis, one can become very familiar with the system that has been modelled. One must realize that the system behaviour is heavily dependent on the type of model derived or chosen and the degree of sophistication as well as the level of mathematics used.

A non-linear model is considered to be more realistic than a linear one, and a distributed parameter model is more accurate than a lumped parameter model. Using a completely mixed flow reactor is one type of representation used in aeration design, but it is only an approximation of real system behaviour. The advantage of using the plug flow model is the ease at which the differential equations can be solved. Physically, this model does not take backmixing, dispersion and holdup into account. To utilize these phenomena information on the exact system size, shape and flow profiles are necessary. The degree of mixing and dispersion can usually be obtained from tracer studies for particular tank and flow configurations. Mixing can be accounted for in several ways. One method involves modification of the state equation to include convective and dispersive terms with coefficients determined from tracer date, i.e., partial differential equations of the form,

$$\frac{\partial \underset{\sim}{x}}{\partial t} = \underset{\sim}{f}(\underset{\sim}{x}, \frac{\partial \underset{\sim}{x}}{\partial \underset{\sim}{r}}, \frac{\partial^2 \underset{\sim}{x}}{\partial \underset{\sim}{r}^2}, \underset{\sim}{u}\ t)$$

where $\underset{\sim}{r}$ is a position vector. The other technique is to consider the dispersion process in terms of a time lag by introducing a time delay variable, θ', which can be estimated from tracer studies. The state equation will then be,

$$\frac{d\underset{\sim}{x}}{dt} = \underset{\sim}{f}(\underset{\sim}{x}, \underset{\sim}{x}(t - \theta'), \underset{\sim}{u}, t),$$

which can be applied to the control optimization procedure.

The considerations involved in determining the optimal control and the control law allows one to observe that system performance can be improved to a great extent when compared to the uncontrolled system, both from an effluent point of view, and from an economic standpoint.

For any new plants, or any old ones which are to be modified, automation should be examined by computer simulation and synthesis to justify its application.

6.0 FUTURE DEVELOPMENTS IN COMPUTER CONTROL

With the advent of integrated circuits, a computer on a chip costing less than $20 is a reality. Full computer systems with 8K of memory are priced at less than $2,000. Computer control and data handling for waste treatment systems are becoming more popular due to price decline and the small sizes available.

Another facet of computer control is to use one central computer in an area with data coming in from as many as 20 wastewater plants, and control signals being sent back. Transmission lines between the plants and the computer are now also unnecessary since the data can be transmitted back and forth by microwave transmitters. The cost of data transmission has also been reduced because of integrated circuit applications and other advances in pulse code modulation and packet radio.

Packet radio is a name given to the time-division multiplexing of a radio channel.[41] Large numbers of users can share one channel without interference. The name "packet" is derived from the fact that each transmission is sent in a package. It has three parts: the address and return address called the "header", the data or message part, and the "trailer", which is an error detection scheme. Packets are sent 25 to 25,000 times faster than teletype. Each message unit is sent in a burst at baud rate of 2,000 instead of 45 as in teletype. Packets are digitally encoded; that is teletype, voice, television, etc. are sent digitally.

The equipment used involves a microprocessor-controlled terminal which could be a TV typewriter or a teletype machine. At the other end, a terminal will receive the packet and look at the address. If the packet is addressed to someone else, the terminal will dump it. Otherwise, it will check for transmission errors and, if the message is intact, the terminal will print it out or display it on the screen.

Systems already involved in packet switching and packet radio are the ARPANET and ALOHA systems. Further details on operation and protocol can be found in the IEEE Journal on Communications.[42] Again, the main idea is to control and log data at a central computer system.

7.0 CONCLUSIONS AND RECOMMENDATIONS

As described in the literature, automatic controls in wastewater treatment plants should produce more carefully controlled effluents, savings in processing chemicals and materials, reduction in energy requirements, continuous data monitoring, and system reliability.

Feasibility studies and preliminary design data can be obtained by simulation of the system on a computer. Control synthesis and values of gain can be calculated concurrently with the simulation studies as well as sensitivity analyses.

The behaviour of different control strategies can be compared by examination of the final values of the performance index, provided it is of the same form for each trial. In this manner, the optimal control policy may be determined.

The degree of sophistication of the mathematical model plays a major role in determining how close the model fits the actual system. In most cases, a well-posed unsteady state mass balance coupled with the proper kinetic can produce a system representation that will produce meaningful results. It is recommended that this type of computer simulation be utilized for feasibility studies for new plant design or if upgrading is contemplated for old ones.

Packet transmission of data and control information can provide a viable means of system operation from a central remote computer. This type of data transmission should be considered if computer operation is to be utilized.

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